

Multi-PeV Signals from a New Astrophysical Neutrino Flux Beyond the Glashow Resonance

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(Dated: May 26, 2016)

The IceCube neutrino discovery was punctuated by three showers with $E_\nu \approx 1-2$ PeV. Interest is intense in possible fluxes at higher energies, though a marked lack of $E_\nu \approx 6$ PeV Glashow resonance events implies a spectrum that is soft and/or cutoff below \sim few PeV. However, IceCube recently reported a through-going track event depositing 2.6 ± 0.3 PeV. A muon depositing so much energy can imply $E_{\nu_\mu} \gtrsim 10$ PeV. We show that extending the soft $E_\nu^{-2.6}$ spectral fit from TeV–PeV data is unlikely to yield such an event. Alternatively, a tau can deposit this much energy, though requiring $E_{\nu_\tau} \sim 10\times$ higher. We find that either scenario hints at a new flux, with the hierarchy of ν_μ and ν_τ energies suggesting a window into astrophysical neutrinos at $E_\nu \sim 100$ PeV if a tau. We address implications, including for ultrahigh-energy cosmic-ray and neutrino origins.

PACS numbers: 98.70.-f, 98.70.Rz, 98.70.Sa, 95.85.Ry

Introduction: The discovery of astrophysical neutrinos by the km³ IceCube detector [1–8] allows for new ways to characterize the high-energy universe. Neutrinos can arise from cosmic-ray interactions within sources (e.g., [9–48]) and with extragalactic photon backgrounds (e.g., [49–55]). The fluxes vary greatly depending on assumptions and data may yield insight into the inner workings of the cosmic-ray accelerators [56] or possible unexpected physical effects [57–70].

There is thus naturally a great deal of interest in neutrino fluxes at very-high energies. In addition to dozens of events in the ~ 10 –100 TeV range, IceCube detected three contained-vertex shower events with deposited energy $E_{\text{dep}} \approx 1-2$ PeV [1, 3]. As shown in Fig. 1, the neutrino spectrum indicated below PeV energies is significantly softer than E_ν^{-2} , reaching at $E_\nu \gtrsim 5$ PeV ($= 5 \times 10^6$ GeV) a sharp upper limit due to a lack of ~ 6 PeV Glashow resonance [71] showers.

However, IceCube has recently reported on a through-going track signal in June 2014 that deposited $E_{\text{dep}} = 2.6 \pm 0.3$ PeV [8]. While all three of the PeV showers arrived from downgoing directions, this track was upgoing from $\sim 11.5^\circ$ below the horizon [8], although we will see that the neutrino energy is likely much larger than that of the shower events. This highest-energy event immediately raises questions, e.g.: what flavor of neutrino produces such a track? What are implications for astrophysical neutrinos in light of prior discoveries?

We first consider the standard assumption that the track is left by a through-going muon. We show that it is unlikely that the present best-fit astrophysical neutrino spectrum, $E_\nu^{-2.6}$, produces such a muon (Fig. 2). This motivates us here to better characterize the super-Glashow energy regime. We consider heuristic spectral models covering a wide variety of neutrino production scenarios and their expected signals.

We also examine an intriguing possibility of a track left by a tau lepton. Though various detection methods for ν_τ have been discussed over many years, including the effect of ν_τ regeneration (e.g., [72–83]), no distinct τ -like signal has yet been identified by IceCube [84]. Energy deposition by taus within the detector leads to many possible signals (see [83]). However, through-going tau tracks are little discussed

and stochasticity in energy losses leave it difficult to individually identify a PeV track as a muon or a very-long-lived tau with decay length $\gamma_\tau c \tau_\tau \approx (E_\tau/20 \text{ PeV}) \text{ km} > 1 \text{ km}$.

For either scenario, we deduce a harder, higher-energy astrophysical neutrino flux than previously measured is more likely present. A tau track traversing the ~ 1 km detector without decaying would imply a much-higher parent neutrino energy, and give an unexpected window into astrophysical neutrinos at energies of ~ 100 PeV. We also address differences in both the energy spectrum and angular distribution of tau and muon events and discuss implications for outstanding problems in cosmic-ray and neutrino physics.

Super-Glashow Fluxes: The neutrino spectrum from pp scattering roughly traces that of the proton spectrum within the source. Spectra from $p\gamma$ scattering, set principally by protons and target photons above the photopion threshold, tend to

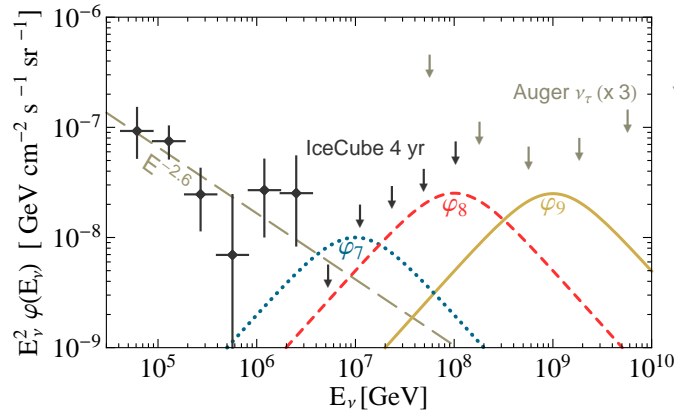


FIG. 1: IceCube 4 yr contained data [5] (which do *not* include the $E_{\text{dep}} = 2.6 \pm 0.3$ PeV track event [8]) and upper limits from Auger ν_τ search [85]. These are compared to an $E_\nu^{-2.6}$ flux (long-dashed) and extragalactic spectral models with peaks near 10^7 GeV (φ_7 ; dotted), 10^8 GeV (φ_8 ; dashed), and 10^9 GeV (φ_9 ; solid). Models φ_7 and φ_8 are similar to spectra from BL Lac AGN models, while combinations of φ_7 and φ_9 can approximate GZK neutrinos from EBL and CMB interactions, respectively. All data and fluxes are summed over flavors (and $\nu + \bar{\nu}$), assuming $\varphi_{\nu_e} = \varphi_{\nu_\mu} = \varphi_{\nu_\tau}$ and $\varphi_\nu = \varphi_{\bar{\nu}}$.

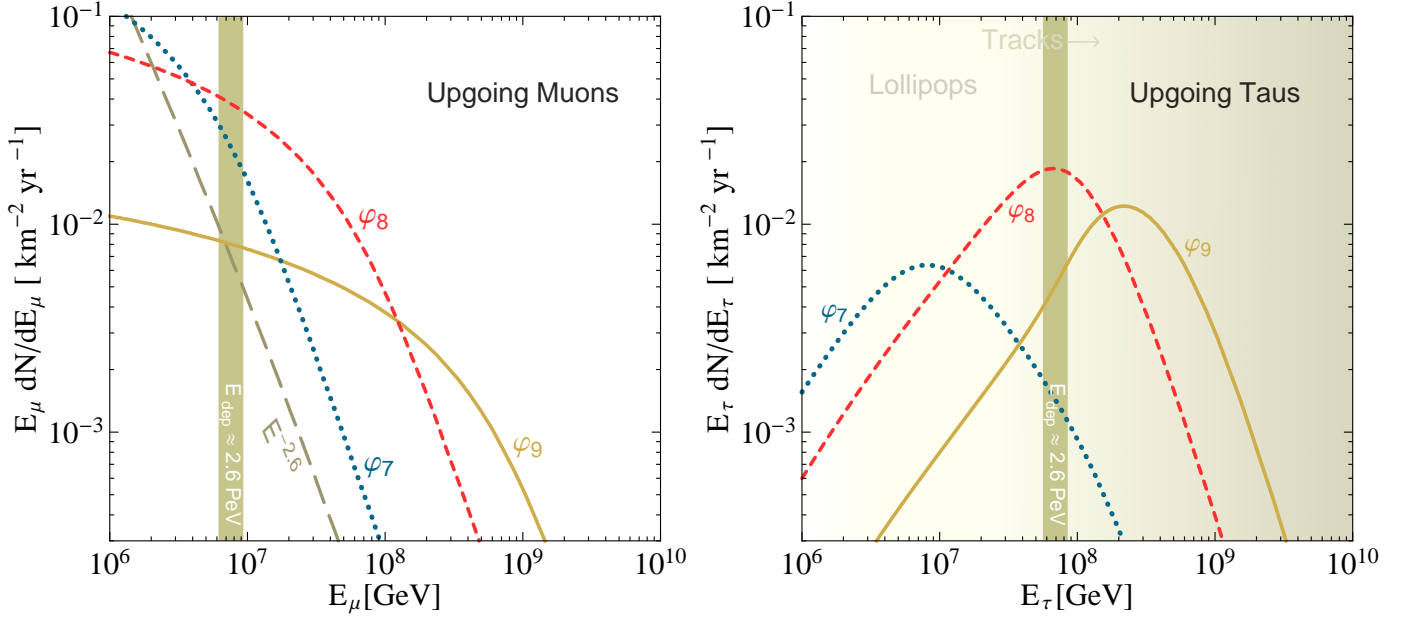


FIG. 2: *Left:* Spectra of upgoing muons with E_μ (energy at entrance to the detector) from model neutrino fluxes in Fig. 1. To deposit ~ 2.6 PeV suggests $E_\mu \gtrsim 8$ PeV (indicated by the vertical band), with a $\gtrsim 10$ PeV requisite energy of the ν_μ . *Right:* The same for taus, with ranges corresponding to dominant entering-tau event topologies denoted. To deposit ~ 2.6 PeV in this case suggests $E_\tau \gtrsim 70$ PeV (vertical band). Note that the required neutrino energy yielding a through-going tau lepton of the same deposited energy as a muon is much larger.

be hard prior to being broken and/or cutoff.

Along with an $E_\nu^{-2.6}$ spectrum similar to IceCube fits [4, 5], we consider model spectra for plausible super-Glashow fluxes at Earth described as smoothly-broken power laws

$$\varphi_i(E_\nu) = f_i \left[(E_\nu/E_i)^{\alpha\eta} + (E_\nu/E_i)^{\beta\eta} \right]^{1/\eta}, \quad (1)$$

with slopes $\alpha = -1$ and $\beta = -3$, broken at $E_i = 10^7$, 10^8 , and 10^9 GeV corresponding to Models φ_7 , φ_8 , and φ_9 , respectively, and using $\eta = -1$ to break smoothly to mimic source variation and cosmic evolution.

These spectra, displayed in Fig. 1, are motivated to describe cosmic neutrino scenarios via suitable combinations of fluxes, with each f_i chosen with IceCube [5] and Auger [85] flux limits (base of the arrows) in mind. Models φ_7 and φ_8 approximate the shape of neutrino spectra from $p\gamma$ photopion production, peaking similarly to High-energy-peaked BL Lac (HBL) and Low-energy-peaked BL Lac (LBL) AGN spectral models [25, 41]. These can be summed with normalizations varied as desired for model-dependent descriptions. We later address relations to ultrahigh-energy cosmic-ray (UHECR) data [86–89] as neutrons must also be produced.

Model φ_9 resembles the GZK (cosmogenic) neutrino spectrum from $p\gamma$ interactions on the CMB, while φ_7 flux can be repurposed for interactions involving lower-energy protons with the extragalactic background light (EBL). The particular combination shown in Fig. 1 is similar to a scenario with a proton dominated UHECR composition to $E_p \gtrsim 10^{20}$ eV with no redshift evolution so that $\varphi_9 + \varphi_7 \approx \varphi_{\text{GZK}}$.

Multi-PeV Spectra: We use these models to estimate rates of neutrino interaction channels in IceCube. For instance,

analytic methods have been presented for shower-like events [27, 29]. While muon fluxes from ν_μ interactions can be calculated [90–92], these cannot be directly applied to taus, due to the much shorter tau decay lifetime.

We determine the spectrum dN_τ/dE_τ of the tau flux through a plane in the ice starting from a continuity equation for taus produced by ν_τ via a volumetric source term $Q(E_\tau)$

$$\frac{d}{dE_\tau} \left[b_\tau(E_\tau) \frac{dN_\tau}{dE_\tau} \right] + \frac{m_\tau}{c \tau_\tau E_\tau} \frac{dN_\tau}{dE_\tau} = Q(E_\tau), \quad (2)$$

with tau energy loss $b_\tau(E_\tau) = dE_\tau/dX$, tau mass m_τ , and tau lifetime τ_τ . We find $b_\tau(E_\tau) = b_0 \rho (E_\tau/\text{GeV})^{\kappa_\tau}$, within a medium of density ρ with $b_0 = -4.6 \times 10^{-9} \text{ GeV cm}^2 \text{ g}^{-1}$ and $\kappa_\tau = 5/4$, adequately approximates the parametrized Monte Carlo results of [82] in our E_τ range of interest. This form is also simple to implement in solving Eq. (2), which can then be rewritten in a form amenable to an integrating factor solution (e.g., [93]). After simplification, we obtain

$$\begin{aligned} \frac{dN_\tau}{dE_\tau} &= \frac{1}{-b_\tau(E_\tau)} \exp \left[\frac{m_\tau}{c \tau_\tau \kappa_\tau b_\tau(E_\tau)} \right] \\ &\times \int_{E_\tau}^{E_\tau^{\text{max}}} dE Q(E) \exp \left[-\frac{m_\tau}{c \tau_\tau \kappa_\tau b_\tau(E)} \right]. \end{aligned} \quad (3)$$

Considering muons, $\tau_\mu \gg \tau_\tau$ so the exponential terms can be neglected, while muon energy loss is typically described as $b_\mu(E_\mu) = -\alpha_\mu - \beta_\mu E_\mu$. We use parameters from the stochastic loss fit for ice in [94], $\alpha_\mu = 2.49 \times 10^{-3} \text{ GeV cm}^2 \text{ g}^{-1}$ and $\beta_\mu = 4.22 \times 10^{-6} \text{ cm}^2 \text{ g}^{-1}$, though deviations can occur at high energies depending on photonuclear losses.

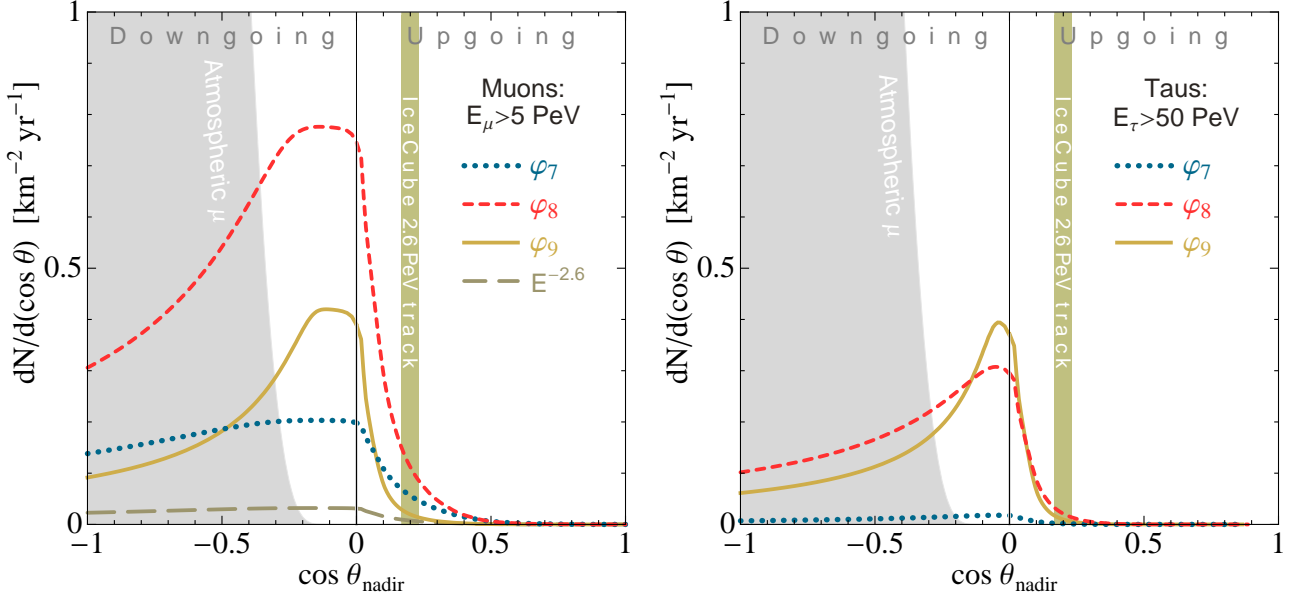


FIG. 3: *Left*: Angular distribution of $E_\mu > 5$ PeV muons for neutrino models in Fig. 1. *Right*: The same for $E_\tau > 50$ PeV taus. The cutoffs towards larger upgoing angles is due to Earth attenuation, while the decline to larger downgoing angles is due to the finite ice depth. Both are compared to the direction of the track event ($\theta_{\text{nadir}} \approx 78.5^\circ$) and background atmospheric muons with $E_\mu > 5$ PeV at the detector (*shaded*).

We first consider downgoing events, for which the fluxes involved are simpler. At PeV and greater energies the differential νN charged-current cross section $d\sigma_{\text{CC}}/dy$ is strongly peaked at $y=0$ [95]. We use $E_\tau = \langle 1-y \rangle E_\nu$, approximating $\langle 1-y \rangle = 0.8 = q$ (ignoring weak E_ν dependence [95]), so that

$$Q(E_\tau) \approx N_A \rho \varphi_\tau(E_\tau/q) \sigma_{\text{CC}}(E_\tau/q)/q, \quad (4)$$

where $N_A \rho$ is the molar density of ice. We find this provides an adequate approximation to the birth spectrum of taus (and muons) using the differential cross section.

E_τ^{max} in Eq. (3) relates the energy at the detector to a birth energy at the ice surface. The particle range determined from an arbitrary energy loss formulation can be inverted (as in [96]), though the simplified parametrizations above allow for analytic solutions. For taus, $E_\tau^{\text{max}} = [E_\tau^{-1/4} + b_0 \ell(\theta)/4]^{-4}$ from our $b_\tau(E_\tau)$, where $\ell(\theta)$ is the column depth to the surface at θ in cm w.e. (we assume an ice depth of 2 km). For muons, $E_\mu^{\text{max}} = \{\exp[\beta_\mu \ell(\theta)](\alpha_\mu + \beta_\mu E_\mu) - \alpha_\mu\} / \beta_\mu$.

For upgoing taus and muons, effectively $E^{\text{max}} \rightarrow \infty$. We also account for Earth attenuation of the neutrino flux, $e^{-\tau_\oplus}$, with $\tau_\oplus = N_A \ell_\oplus(\theta) \sigma_{\text{tot}}(E_\nu)$ using $\ell(\theta)$ from the Preliminary Reference Earth Model [97]. For ν_e and ν_μ , $\sigma_{\text{tot}} = \sigma_{\nu N}$. For $\bar{\nu}_\mu$, $\sigma_{\text{tot}} = \sigma_{\bar{\nu} N}$, although for $\bar{\nu}_e$ we must include $\sigma_{\bar{\nu} e}$.

Upgoing ν_τ fluxes are complicated by regeneration due to the relatively-quick decays of taus produced in CC interactions back into ν_τ . The total number flux of ν_τ is conserved, although the spectrum is distorted towards lower E_{ν_τ} . We estimate the surviving ν_τ flux by converting the interacting fraction for each E_{ν_τ} into a continuous distribution based on [81] (neglecting regenerated ν_μ and ν_e).

Multi-PeV Rates: Fig. 2 shows the flux of muons (*left*)

and taus (*right*) versus energy as they enter the detector arising from the models in Fig. 1. It is evident that the $E_\nu^{-2.6}$ spectrum yields a very-low rate of multi-PeV muons (and a negligible tau rate not shown), though it would be useful to have a quantitative comparison with observations.

The neutrino energy probed by a fully-through-going track event depends on the flavor of the parent neutrino. If the 2.6 ± 0.3 PeV track event is due to a muon, estimating the deposition in ~ 1 km by integrating the above $b_\mu(E_\mu)$ implies $E_\mu \gtrsim 8$ PeV upon entrance to IceCube, indicated by the vertical band in the left panel of Fig. 2.

Compared to a muon with the same energy, the energy loss rate of a tau is much smaller. To deposit $E_{\text{dep}} = 2.6$ PeV in ~ 1 km using $b_\tau(E_\tau)$ alone (i.e., not including any energy from the ν_τ interaction or tau decay, both assumed to occur outside the detector) implies $E_\tau \approx 67$ PeV. The light yield may even be less than a muon of this E_{dep} dependent upon photonuclear losses [83]. This difference in neutrino energy for $E_\tau \gg E_\mu$ required for a through-going tau track is significant.

Muon and tau energy deposition are more or less stochastic (e.g., [94, 98]). For concreteness, we consider rates for $E_\mu > 5$ PeV and $E_\tau > 50$ PeV to allow for fluctuations in the light yield of a particular event. This still corresponds to energies for which the tau can traverse IceCube before decaying.

In $5 \text{ km}^2 \text{ yr}$, the $E_\nu^{-2.6}$ model yields only 0.04 upgoing $E_\mu > 5$ PeV muons. For φ_7 , φ_8 , and φ_9 , we find 0.14, 0.35, and 0.12 upgoing muons and 0.01, 0.13, and 0.12 $E_\tau > 50$ PeV taus, respectively. Downgoing muons and taus are in the range of 1–2, depending on cut angle, as we detail later. We examine other channels for consistency. The rate of $E_{\text{dep}} > 5$ PeV showers in $5 \text{ km}^3 \text{ yr}$, calculated as in [27, 29], for $E_\nu^{-2.6}$ is again small. For φ_7 , φ_8 , and φ_9 , we find 1.7,

0.6, and 0.06 from $\bar{\nu}_e e$; 0.6, 0.8, and 0.2 from $\nu_e N + \bar{\nu}_e N$; 0.1, 0.5, and 0.2 neutral current, respectively. Comparing to IceCube UHE neutrino effective areas [99] these appear consistent within variations with energy.

The spectra in Fig. 2 are left as raw fluxes without attempting to correct for IceCube energy resolution. While for muons this would be fairly straightforward, with event reconstruction yielding better resolution at high energies [98], for taus the correspondence between energy and decay length complicates the effect on event topologies. We indicate in Fig. 2 the energy ranges characteristic of entering-tau event classes: “lollipops” in which a tau enters the detector and decays (i.e., in the last ~ 1 km of its range) and “tracks” that traverse the entire detector prior to decay. Overestimating the tau energy, for instance, does not result in an increase in its actual range and would not change the topology. Also, uncertainty in tau photonuclear losses affects the expected visible signal in IceCube [83].

The energies required to deposit ~ 2.6 PeV as calculated here are indicative and a more thorough investigation should be carried out by IceCube. We note that IceCube muon measurements have suggested a hard $E_{\nu\mu}^{-2}$ spectrum for ν_μ , though only in a $E_{\nu\mu} \approx 150 - 3000$ TeV window [6, 7]. A muon depositing much more than average energy, with lower implied E_ν , leaves the question of why $\bar{\nu}_e e$ events are yet unseen. (Though a flux from $\pi^+ \mu^+$ decays alone, with $\varphi_{\nu_e} \gtrsim 3 \varphi_{\bar{\nu}_e}$, would cut the Glashow rate by \sim half; see [27].) The huge Earth attenuation due to $\sigma_{\bar{\nu}_e e}$ disfavors an upgoing muon from a Glashow resonance $W^- \rightarrow \mu^- \bar{\nu}_\mu$ decay.

Even with a more precise calculation, our conclusion will remain valid: the energy of a tau must be much larger than that of a muon in order to deposit the same amount of energy within the detector volume. The τ track signal is often neglected (c.f., [72]), and even if this track turns out to favor a muon, we encourage optimizing tools for through-going taus.

Implications and Conclusions: Even a single such highly-energetic track event gives a first direct hint of an astrophysical neutrino flux beyond that already firmly discovered. For $E_\nu \gtrsim 10$ PeV we are beyond the Glashow resonance. A track event due to a tau gives us insight into the astrophysical neutrino spectrum at energies approaching $E_\nu \sim 100$ PeV.

The rates from our spectral models are in plausible ranges to source a track event; however, puzzles remain. For instance, the φ_7 rate of $\bar{\nu}_e e$ events does not leave room to raise flux normalization to increase its muon rate and it yields few τ tracks. Events from φ_9 tend toward very-high energies. Model φ_8 yields the most muons and a sizable τ track fraction.

Angular Distributions: Fig. 3 compares the angular distributions for our model fluxes of muons with $E_\mu > 5$ PeV and through-going $E_\tau > 50$ PeV taus. IceCube expects to see some PeV muons from cosmic-ray interactions in the atmosphere. We estimate this background by relating the muon spectrum at the ice surface to that reaching the detector accounting for energy loss (e.g., [90]). Being concerned with PeV energies and above, we use a spectrum approximate to the prompt flux in IceCube [100], taking $dN/dE_\mu \propto E_\mu^{-3}$, neglecting muon bundles (discussed by IceCube [100]).

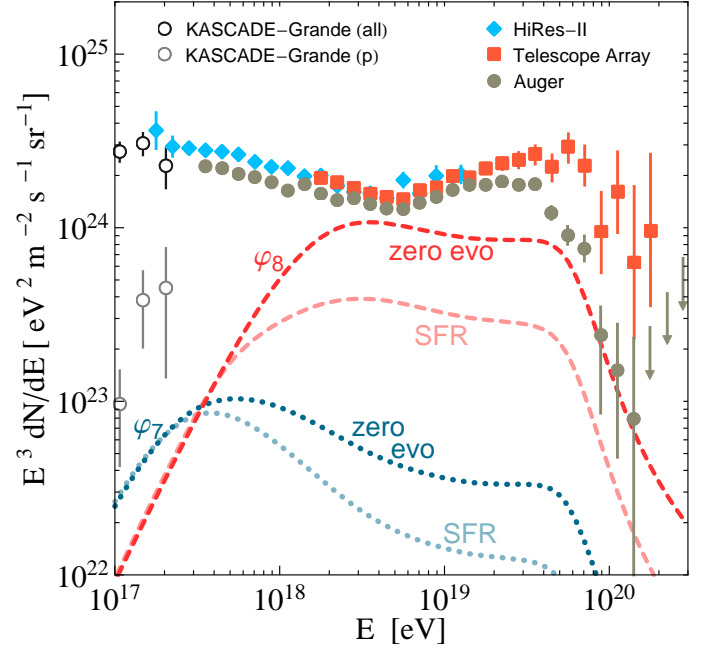


FIG. 4: The ultrahigh-energy cosmic-ray spectrum. Shown are proton fluxes associated with neutrino Models 7 (dotted) and 8 (dashed) assuming zero (dark) or star formation rate (light) source evolution. These are compared to KASCADE-Grande (all and proton-like) [86], HiRes-II [87], Auger [88], and Telescope Array [89] data.

In Fig. 3, we also show the angular distribution of atmospheric muons with $E_\mu > 5$ PeV at the detector depth. We see the region that is effectively background limited by these muons. The column of ice is sufficient to effectively eliminate these as background at angles $\lesssim 10^\circ$ above the horizon, with the direction of the track being well below this range. A prompt PeV neutrino flux should be steeper with a lower normalization than the $E_\nu^{-2.6}$ model [5, 101], with a $< 0.01\%$ probability of an atmospheric origin for the track event [8].

Standard Model and Beyond: While we quote event rates above for all upgoing directions, the 2.6 ± 0.3 PeV track event comes from a relatively large angle below the horizon. This becomes suspicious if similar tracks are not soon detected from downgoing and shallower angles. We have seen that the cutoffs in the Fig. 3 angular distributions are flattened if Earth opacity is decreased. This could occur if $\sigma_{CC}(E_\nu)$ saturates at \gtrsim PeV due to non-linear small- x QCD effects (e.g., [102]).

New-physics effects are also confronted. We note here that a multi-PeV track is already at odds with some neutrino decay models [103, 104]. It also pushes back bounds on Lorentz invariance violating scenarios (e.g., [57–61]). We defer more detailed examination of event flavor ratios to elsewhere.

UHECR Connections: Cosmic neutrino emissivities for each φ_i can be obtained from a suitable source dN_ν/dE_ν as

$$\varphi_\nu(E_\nu) = \frac{c}{4\pi} \int_0^{z_{max}} \frac{dN_\nu}{dE'_\nu} \frac{dE'_\nu}{dE_\nu} \frac{W(z)}{dz/dt} dz, \quad (5)$$

where $dz/dt = H_0 (1+z)[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}$, ($\Omega_m = 0.3$,

$\Omega_\Lambda = 0.7$, and $H_0 = 70$ km/s/Mpc), and $dE'_\nu/dE_\nu = (1 + z)$, accounting for source evolution with redshift, $\mathcal{W}(z)$, with appropriate adjustments of the spectral parameters (see [42]). This assumes an isotropic neutrino flux (we discuss origins from a bright source and the Milky Way in Appendix).

We assume $\pi^\pm\mu^\pm$ decays yield six neutrinos for each neutron of $E_n \sim 20 E_\nu$ decaying to a proton with $E_p \approx E_n$ [27]. Taking optically-thin sources, such as BL Lacs [41] that motivate φ_7 and φ_8 , we calculate proton spectra as in [27]. We do not use φ_9 here as it is motivated by GZK neutrino fluxes and thus connected to a UHECR proton flux by construction.

Fig. 4 shows the resulting flux of UHECR cosmic-ray protons at Earth for φ_7 and φ_8 for zero, as often assumed for BL Lacs, or cosmic star formation rate (SFR) [105–107] evolution, with no high-energy cutoff to the $\beta = -3$ spectrum. These fall below the data, though φ_8 is close at $\gtrsim 10^{18}$ eV where the composition is light [108–110]. Assuming fewer pions per neutron would raise each proportionately [27], though saturating the data would leave no room for UHECR mechanisms other than neutron escape from IceCube sources.

Conclusions: The $E_{\text{dep}} \approx 2.6 \pm 0.3$ PeV IceCube track event implies the highest E_ν interaction to date. Our calculations suggest it is unlikely that the soft spectrum of neutrinos accountable for the ~ 40 TeV to ~ 2 PeV IceCube events can produce such a track. If this track event is due to a muon, it may indicate a parent neutrino energy of $\gtrsim 10$ PeV. Alternatively, a through-going tau leaving such a track can suggest a neutrino energy in the ~ 100 PeV range, giving a window into the astrophysical neutrino flux at unexpectedly-high energies.

This huge separation of the parent neutrino energies in producing a through-going track with the same energy deposition is a point to be reiterated. It highlights the importance of identifying the parent charged lepton for an individual track event. The very-low rate of such events from the best-fit $E_\nu^{-2.6}$ power-law flux favors a new astrophysical neutrino flux reaching beyond the Glashow resonance.

The models that we considered suggest that the IceCube multi-PeV track may be just the tip of a super-Glashow iceberg. We note that ANITA recently reported a 600 ± 400 PeV shower event that could be from a tau decaying above the ice, though being $\gtrsim 20^\circ$ upgoing is even more perplexing [111]. Many taus sufficiently-energetic to result in through-going tracks in IceCube would be contained within a next-generation detector [112], so more distinctive topologies [73, 78, 83] would be resolved. Along with detectors such as ARIANNA [113] and ARA [114], this raises prospects of addressing flavor ratios, the birthplaces of UHECR, and more.

We thank Amol Dighe, Alex Friedland, Raj Gandhi, Francis Halzen, Claudio Kopper, John Learned, Kenny C.Y. Ng, Tyce de Young, and especially John Beacom and Hasan Yüksel for discussions and INT Program INT-15-2a “Neutrino Astrophysics and Fundamental Properties” for hospitality during a portion of this project. MDK and RL acknowledge support provided by Department of Energy contract DE-AC02-76SF00515 and the KIPAC Kavli Fellowship made possible

by The Kavli Foundation.

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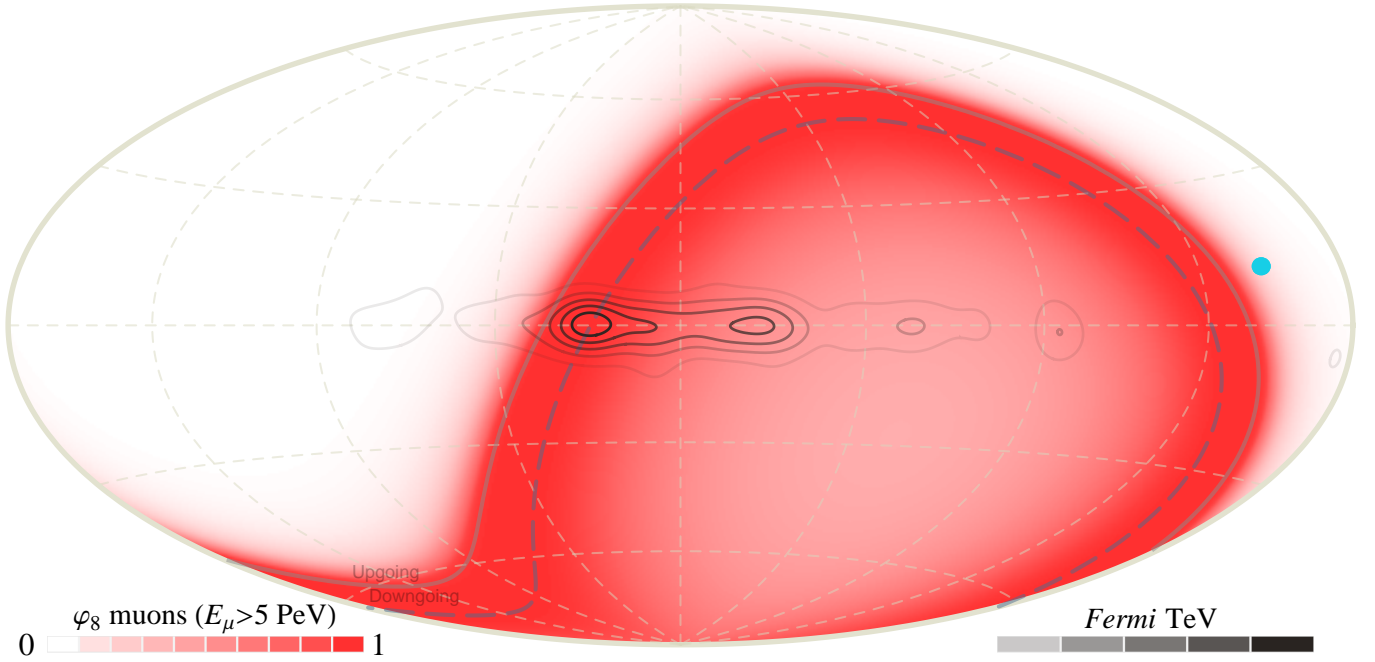


FIG. 5: Sky density of $E_\mu > 5$ PeV muons from model φ_8 (in Galactic coordinates; *shaded*). The horizon (*solid*) demarcates upgoing and downgoing directions, with the rough 10° downgoing boundary for atmospheric muons (*dashed*). The $E_{\text{dep}} \approx 2.6$ PeV IceCube track event (*blue dot*) and contours of $E_\gamma > 1$ TeV *Fermi* emission smoothed by 5° from [70] are shown for reference.

Appendix: Multi-PeV Origins

Fig. 5 shows the muon sky density arising from our φ_8 flux model, with a dashed curve 10° above the horizon. We have assumed isotropic neutrino fluxes here and elsewhere, although if the multi-PeV IceCube track arose from emission within the Milky Way or a particularly bright source conclusions could be rather different.

Could this event actually be Galactic? $E_\nu \gtrsim 10$ PeV implies a proton energy $E_p \gtrsim 10^{17}$ eV, well beyond the cosmic-ray proton knee (for nuclei of mass number A , we would need to consider E/A). If such neutrino emission resembles that of TeV gamma rays in *Fermi* ([70]; see Fig. 5), we would expect a much higher rate nearer the Galactic Center (GC). Such a flux gradient outwards from the GC also increases the expected downgoing/upgoing ratio due to the location of IceCube. That being said, while a location $\sim 12^\circ$ from the Galactic plane does not indicate Galactic emission, it is somewhat unlikely if projecting a $\sim \pm 10^\circ$ band around the IceCube horizon.

BL Lac origins have been discussed for each of the three $E_{\text{dep}} \approx 1\text{--}2$ PeV shower events (e.g., [115–118]), though the angular resolution of such events is limited to $\gtrsim 10^\circ$. However, the 2.6 PeV track is localized to 1° at 99% uncertainty [8].

Around the best-fit IceCube track position we do not identify any notable object within 1° . At $\sim 2^\circ$ is PMN J0717+0941, a relatively-nearby (~ 123 Mpc) radio galaxy [119]. At $\sim 3^\circ$ is the nearest *Fermi* BL Lac, 4C 14.23 [120]. No gamma-ray source was reported by HAWC [121]. This event could be from a faint source, though there is no obvious indication of a prominent super-Glashow neutrino source that would violate an assumption of a diffuse, perhaps cosmogenic, flux.